1980

Compressor originated Noise in a Diving System

G. Rauen

W. Soedel

COMPRESSOR ORIGINATED NOISE IN A DIVING SYSTEM

D. G. Rauen* and W. Soedel, Ray W. Herrick Laboratories
School of Mechanical Engineering, Purdue University
West Lafayette, Indiana 47907, U.S.A.

* Currently with Eaton Corporation, Engineering & Research Center, Southfield, Michigan 48037, U.S.A.

ABSTRACT

Using a four pole model of a diving system, the sound pressure levels in the diver's helmet are predicted, assuming the diving compressor to be the sole noise source. It is shown that the compressor originated noise is an important part of the total noise (some of which is caused by turbulence), if not the most important. Various phenomena experienced by divers are predicted and illustrated.

INTRODUCTION

The particular diving system under study employs a bank of reciprocating compressors to pump the breathing gas to the diver's helmet, and a second bank of compressors to pump the exhaled gas away from the helmet. The pressure pulsations created by these compressor banks travel through the breathing system plumbing which consists of CO_2 scrubbers, filters, heaters, expansion chambers, control valves, umbilical hoses, etc. These pulsations may, of course, be amplified or attenuated as they travel toward the helmet depending upon the system geometry, properties of the breathing gas mixture and the conditions under which the diving system is operating. Several unwanted effects may occur in the diver's helmet:

1. A pressure waveform may be produced which destructively interferes with the diver's breathing pattern causing him to expend undue effort in the breathing process--over and above the effort he must expend to perform his underwater tasks.

2. Under proper conditions, a system resonance may be excited causing large amplitude pressure surges which may damage the diver's body tissues, especially his lung tissue [1]. In the extreme case, it is conceivable that the diver's lungs may burst or collapse.

3. Excessive dynamic back pres ures may be produced in the discharge manifolds [2]; thus reducing the maximum available gas flow rate to the helmet.

4. The noise level produced in the helmet may interfere with or completely obstruct audio communications. Very annoying beat frequencies may also be produced.

5. The helmet noise level may exceed the recommended standards (such as those set by the U.S. Occupational Safety and Health Administration [3]) and possibly damage the diver's ears.

These pressure pulsations can be predicted fairly well with the so-called four-pole method. This method is based upon linearized gas pulsation theory and has been applied most frequently to compressor and engine manifolds [4-6]. This method includes the important effect of acoustic attentuation due to fluid damping and pipe wall friction--an effect that is in most applications neglected since most systems modeled with this method have relatively short pipe lengths (i.e. mufflers). Diving systems, however, use hoses of up to several hundred feet in length and therefore, require this effect to be included in their analysis.

In this study, the four-pole method was applied to a closed-circuit deep sea diving system to determine the helmet response to the input of two compressor banks at various levels of diving depth [7-9]. The model includes the effects of changes in the breathing gas composition (an oxygen-nitrogen-helium mixture), breathing gas temperature, pressure drops due to pipe wall friction and regulating valves and the effects of acoustic attenuation due to fluid damping.

The objectives of the study are to examine the effects of the system geometry, diving depth and breathing gas flow rate on the pressure pulsations produced in the helmet.

One of the contributions of this paper to the state of the art is that the gas pulsations (acoustics) of a deep sea diving system have been analyzed to a point that many phenomena experienced by divers can now be explained and predicted on a theoretical basis. In addition, it is also the first time, in the opinion of the authors, that the gas pulsation complications caused by the staging of two compressor banks have been mathematically formulated and simulated on the computer.

THE PHYSICAL SYSTEM

A closed-circuit, deep-sea diving system [10-13] was analyzed (see Figure 1) in which the breathing gas is continuously reconditioned and recirculated to the diver. The diver wears a suit that exposes him to the ambient water pressure. Therefore, the breathing gas is supplied to him at a mean pressure equal to that of the ambient water pressure. Manual and automatic valves in the helmet and elsewhere within the breathing system are used to accomplish this.

Since high pressures of oxygen and/or nitrogen in the lungs are harmful, helium is added to the air to increase the total pressure of the breathing gas while keeping the partial pressure of the air approximately constant at one atmosphere. In this way, the diver receives the same mass of oxygen and nitrogen in one breath as he would receive at atmospheric conditions. Thus, the composition of the breathing gas mixture is regulated according to the diver's depth (see Figure 2). This causes the speed of sound in the mixture to increase with depth up to three times what it is at atmospheric conditions (Figure 3).

The breathing system equipment necessary to perform these regulations is mounted around and within a diving chamber which is suspended from a ship to depths of up to 1000 feet (305 meters). This diving chamber is referred to as the personal transfer capsule (PTC).

To conserve the helium, the exhaled breathing gas is returned to the PTC for reconditioning and recirculation, rather than being exhausted into the ocean. This closed-circuit design requires a bank of compressors to pump the breathing gas to and away from the diver (see Figure 4). These compressors are encased in a pressure vessel mounted outside the PTC. One bank of compressors termed the "Push" compressors pumps the breathing gas to the diver when he is below the PTC. A second bank of compressors termed the "Pull" compressors pumps the breathing gas away from the diver when he is above the PTC. The diver may regulate the breathing gas flow rate by adjusting a supply valve mounted on his helmet.

HELMET RESPONSE

To model the breathing system shown in Figure 4, some simplifying assumptions were made:

1. Since the valves of any one compressor are never both open at the same instant, the helmet side of the breathing system is assumed to be acoustically isolated from the PTC side of the breathing system. Therefore, only the helmet side of the system need be analyzed to find the helmet response.

2. A worst-case analysis was made by assuming that all eight cylinders of each compressor bank discharge at once (although a phase angle between the two banks was accounted for. See Figure 5). In addition, all eight cylinders of each bank were modeled as one large cylinder of equivalent total displacement volume.

3. The mass flow rate curves for the two equivalent compressors were assumed to have a square wave shape (again, the worst case) whose average value is equal to the design flow rate of the compressors.

4. The tubes and cylinders which form each manifold were modeled as one square cylinder of equivalent volume.

5. The helmet was modeled as a square cylinder with a volume equivalent to the clearance volume in the actual helmet.

The first assumption agrees well with reality. The second assumption reflects the fact that the cylinder discharge sequence was not kinematically controlled, but was a random function of assembly. The third assumption was necessary since anything more precise would have required a detailed modeling of the valve flow. While it can be argued that the resulting deviation might be large when comparing an individual harmonic response magnitude with its experimental counterpart, especially in the high frequency range, comparison with octave band data should be relatively good since in this case the individual differences are averaged over a wide frequency band. Of course, care was taken to make the energy of the square equal to the true pulsation energy input. This can be done using basic thermodynamic reasoning without knowing the precise shape of the wave. In any case, the general tendency of the results should reflect reality fairly well, even when comparing narrow band data. Assumption four becomes questionable in the high frequency range where the dimensions of the volume tanks exceed one quarter of the wavelength, even while it has to be remembered that because of the high speeds of sound at average diving depth wavelength are larger than on the surface. The error that is introduced by this assumption is that cross modes or even longitudinal mode effects in the volume tanks may exist in the experimental data, but are not predicted by the theory. However, experience indicates that cross modes are only weakly excited in similar systems and it is, therefore, felt that the approximation made is an acceptable one for a model whose purpose is to provide mainly insight into the acoustic behavior of a diving system. Assumption five seems to be quite reasonable.

Experimental data was used to estimate the average temperature and mean pressure in each of the elements shown. This information, along with the dimensions of each element, and the operating conditions (diving depth, breathing gas composition, etc.) were used to calculate the four-pole coefficients.

RESULTS

A computer program was written [7] to perform the matrix multiplication. A subroutine converted the discrete frequency spectrum of the SPL in the helmet into octave band form and weighed the results with the A scale. The octave band form was selected because the available experimental data was in this form.

Sensitivity Study

Several preliminary simulations were made to determine the sensitivity of the helmet acoustic pressure to various input parameters. The effect of the pressure distribution throughout the breathing system was examined first. It was found that when the diver is at the PTC depth, one average value of the breathing gas pressure throughout the entire system would give results not significantly different from those when the average pressure of each individual element was used. However, when the diver moves above or below the PTC, the pressure distribution throughout the system changes significantly causing the flow rate at the pumps to change, resulting in helmet SPL changes of up to 10 dB.

The effect of the breathing gas temperature was tested similarly. Results using the average temperature of each element differed by as much as 10 dB from those when one average value of 70°F was used for the entire system.

The effect of the breathing gas viscosity was found to be small at low frequencies and very strong at high frequencies as shown in Figure 6. One observes the expected tendency that oscillation amplitudes diminish with increasing viscosity, and that viscosity is a relatively sensitive parameter. While the top two curves are related to each other as expected, the curve representing ten times the actual viscosity shows the somewhat unexpected effect of a much reduced sound pressure level at a center frequency of 1000 Hz., contrasted to a relatively small reduction at 2000 Hz. The only intuitive explanation that can be offered is that an energy shift has occured between the three frequency bands centered at 1000, 2000, and 4000 Hz. Even ten times the actual viscosity results in very low modal damping and resonance peaks are still expected to occur, even while significantly diminished in magnitude.

Lastly, the kinematic phase angle α between the two compressor banks was tested for its effect. Only the first several harmonics of the compressor speed were affected (See Figure 7) and a 180° phase angle produced the largest predicted pulsations in the helmet at these harmonics. This 180° phase angle was used in all subsequent simulations in keeping with the worst-case analysis approach.

Simulations of the Actual System

The SPL in the diver's helmet is plotted for three different diving depths in Figure 8. The diver is at the PTC depth in all three cases. It is seen that the SPL increases as the system descends to greater depths - a trend that has been observed in actual experiments. This effect may be due to the increase in the speed of sound in the breathing gas as the system descends and the associated larger pulsation energy input from the positive displacement compressor caused by its increased volumetric efficiency. The peaks centered near 250 Hz. and 2 KHz. are characteristic of this particular diving system arrangement.

Figure 9 shows the effect of the diver's depth relative to the PTC. As stated earlier, movement of the diver above or below the PTC causes changes in the pressure distribution throughout the breathing system. The effects of these pressure changes diminish with depth because the average pressure of the system increases.

Lastly, the effect of the breathing gas flow rate through the helmet was investigated. Figure 10 shows that the helmet SPL is predicted to rise with increasing gas flow rate. Experimental data bears this out.

Simulations of System Modifications

The purpose of the volume tanks shown in Figure 4 is to isolate the helmet side of the breathing system from the pressure pulsations created by the two compressor banks. Simulation results shown in Figure 11 show these tanks to be very effective in reducing the helmet SPL, as would be expected. Once again, experiment bears this out.

To test the effect of the umbilical hoses, they were removed from the model system. Figure 12 shows that they serve as fairly good attenuators of the compressor-induced pulsations, especially at frequencies above 500 Hz.

COMPARISON WITH EXPERIMENTAL DATA

Available test data for this particular diving system [13] was taken under the following conditions:

1. The helmet was lined with an absorbent material.
2. A dummy head was installed in the helmet.
3. A microphone was placed in its ear.
4. A breathing machine was connected to the throat of the dummy head and was operated at 20 breaths per minute.
5. A porous tube-type muffler was installed within the helmet to mask the hissing-type noise created by the flow of breathing gas through the supply valve. (The flow noise generated by this valve was examined by the author's in references [14] and [7]).

Under these conditions, the helmet noise spectrum as generated by the compressors is "upset" by the effect of the helmet muffler and the flow noise generated by the breathing machine and helmet exhaust valve. Nevertheless, this data is still useful in verifying the general trends predicted by the simulation.

At a system depth of 200 ft (61m) Figure 13a shows the comparison of the measured and predicted helmet noise levels. The calculated value of the first harmonic is seen to be quite high, but recall that the worst case of 180° cylinder bank phasing was used, which caused the first harmonic to be 20 dB higher than the case of zero phasing. The measured values between 500 Hz. and 8 KHz. are also seen to be higher than predicted. This difference is attributed to the flow generated noise within the helmet which typically occurs within this range. As the system descends, the compressor generated noise increases and eventually supercedes the flow generated noise. At this point, the entire spectrum is dominated by compressor noise and thus, measured and predicted values should more closely agree. Figure 13b bears this out. At a system depth of 600 ft (183m), remarkably good agreement is seen across the spectrum except, of course, for the first harmonic.

The measured data in Figure 13c verifies once again that as the system descends to greater depths, the overall noise level in the helmet increases. Note that the predicted SPL spectrum exhibits two prominent peaks which do not appear in the measured spectrum. Data taken from a similar diving system which was not equipped with a helmet muffler showed these two peaks to be a characteristic of this general type of diving system arrangement. This indicates that the helmet muffler has effectively reduced the unwanted peaks in the helmet spectrum.

SUMMARY AND COMMENTS

The four-pole method of calculating gas pulsations in piping networks has been successfully applied to the breathing circuit of a deep-sea diving system and has been used as a tool for analyzing the system design and the effects of operating conditions. The assumptions made in developing the model such as square wave forcing functions, and equivalent compressors, have produced very reasonable results. Of course, a closer approximation to the actual system could have been obtained by modeling the dynamics of each individual compressor cylinder and the resulting manifold interactions as was done by Singh and Soedel [5] for a two-cylinder compressor discharge system. However, with these simplifying assumptions, the model is easy to program and consumes a very modest computing time of about 20 seconds per run.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Raymond L. Bentz of the Naval Coastal Systems Laboratory for his help during the course of this work. They are also grateful to the Naval Coastal Systems Laboratory for sponsoring this project.

REFERENCES

1. U.S. Navy Diving Manual, 1973, Department of the Navy, Washington, D.C., U.S.A., NAVSHIPS 250-538, Section 1.3. "Underwater Physiology."

2. W. Soedel, D.L. Strader, R.C. Mutyala, 1976, Proceedings of Purdue Compressor Technology Conference, West Lafayette, Indiana, U.S.A., 326-340. "Redesign of Diving Compressor Manifolds to Avoid Excessive Power Usage: A Case Study."

3. U.S. Department of Labor, Workplace Standards Administration, Bureau of Labor Standards, 1970, Title 41, part 50-204, Section 10. "Safety and Health Standards for Federal Supply Contracts."

4. W. Soedel, 1978, Short Course Text, Purdue University, School of Mechanical Engineering. "Gas Pulsations in Compressor and Engine Manifolds."

5. R. Singh, W. Soedel, 1979, Journal of Sound and Vibration, 62, 125-143. "Mathematical Modeling of Multicylinder Compressor Discharge System Interactions."

6. J.P. Elson, W. Soedel, 1974, Journal of Sound and Vibration, 34, 211-220. "Simulation of the Interaction of Compressor Valves with Acoustic Back Pressures in Long Discharge Lines."

7. D.G. Rauen, W. Soedel, 1978, Purdue University, Ray W. Herrick Laboratories, Report HL 78-16. "Simulation of an Underwater Breathing System."

8. F. Laville, W. Soedel, 1976, Purdue University, Ray W. Herrick Laboratories, Report HL 76-31. "Analysis of Diving System from Simplified Viewpoint."

9. D. Strader, R. Mutyala, W. Soedel, 1975, Purdue University, Ray W. Herrick Laboratories, Report HL 75-30, "Compressor Analysis for Mark 14 Diving System."

10. R.L. Bentz, 1975, Naval Coastal Systems Laboratory, Panama City, Florida, 32401. "Mark 14 Push-Pull Underwater Breathing System."

11. Raymond L. Bentz, 1978, Proceedings of the 1978 Working Diver Symposium, Marine Technology Society, Salvage and Diving Committee, 202-210. "Development of the Navy's MARK 14 Closed Circuit Saturation Diving System."

12. Raymond L. Bentz, 1979, Naval Engineers Journal, April, 1979, 91-98. "Development of the Navy Mark 14 Underwater Breathing Apparatus."

13. R.L. Bentz, 1977, Naval Coastal Systems Laboratory, Panama City, Florida, 32401. "Mark 14 CCSDS Unmanned System Tests in the Ocean Simulation Facility."

14. D.G. Rauen, W. Soedel, 1977, Purdue University, Ray W. Herrick Laboratories, HL 78-16. "Aerodynamic Sound Generation with Applications to Underwater Breathing System."

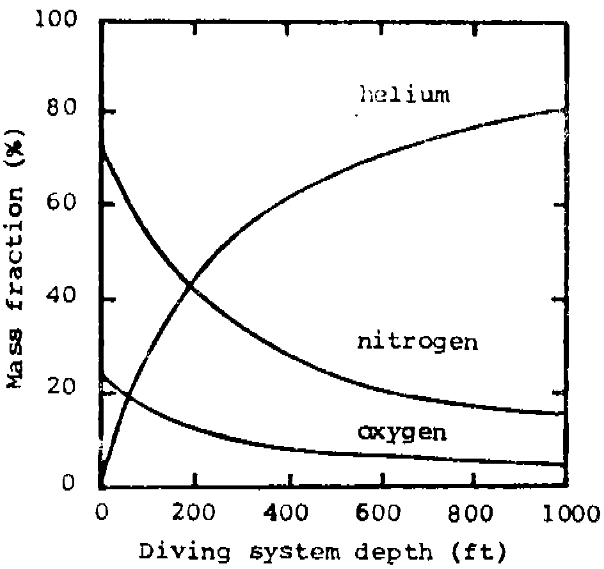


Figure 2. Breathing gas composition as a function of system depth.

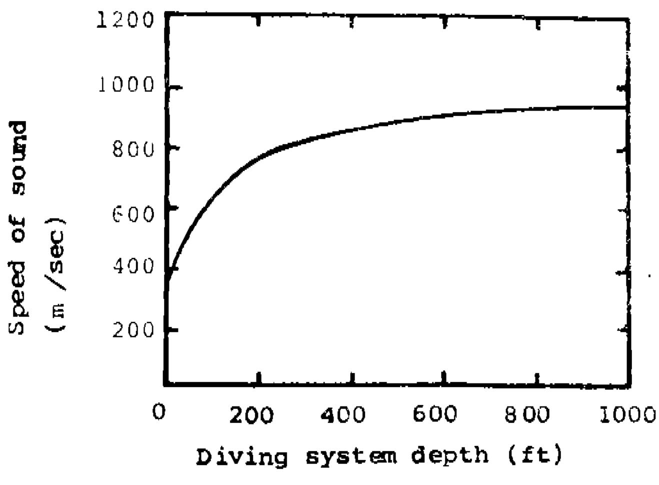


Figure 3. Speed of sound in breathing gas as a function of system depth.

Figure 1

Diving System Arrangement[10,11,12,13]

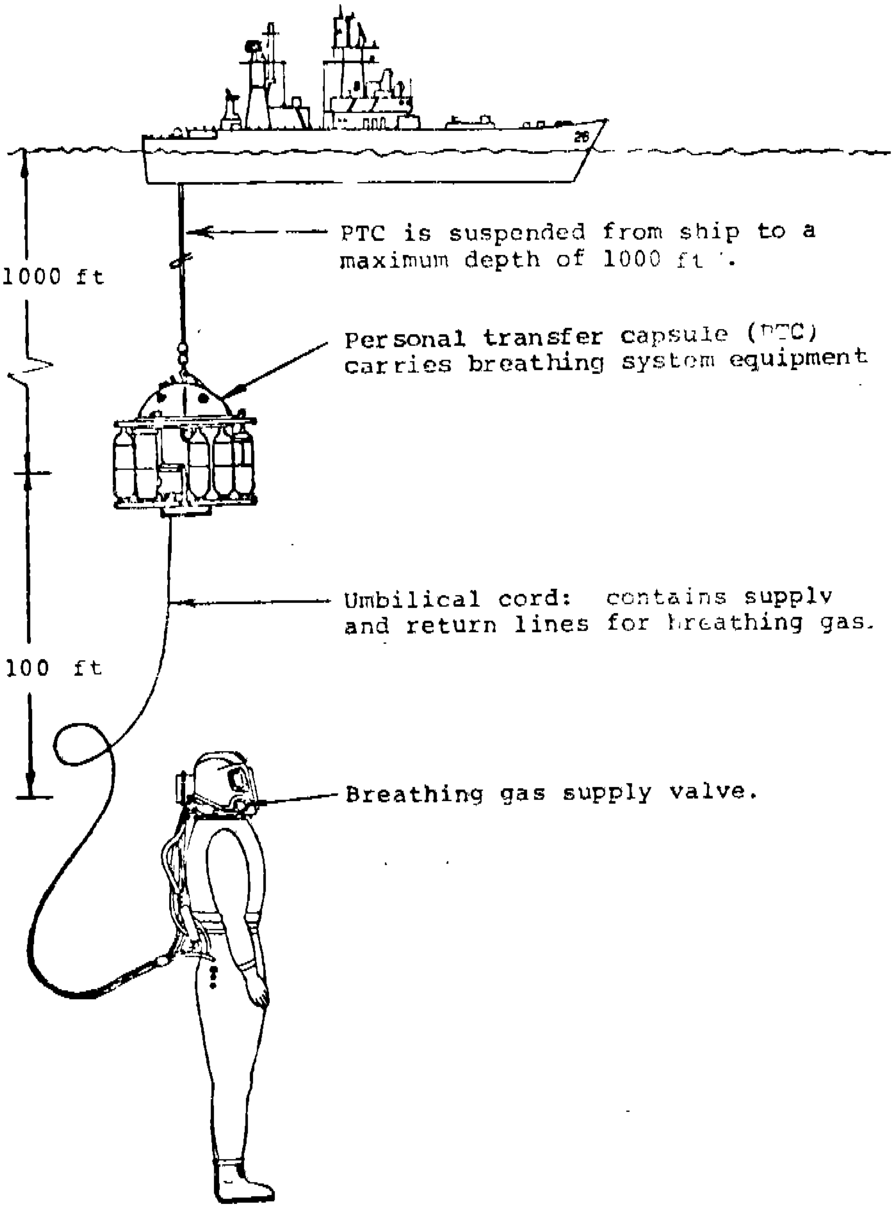
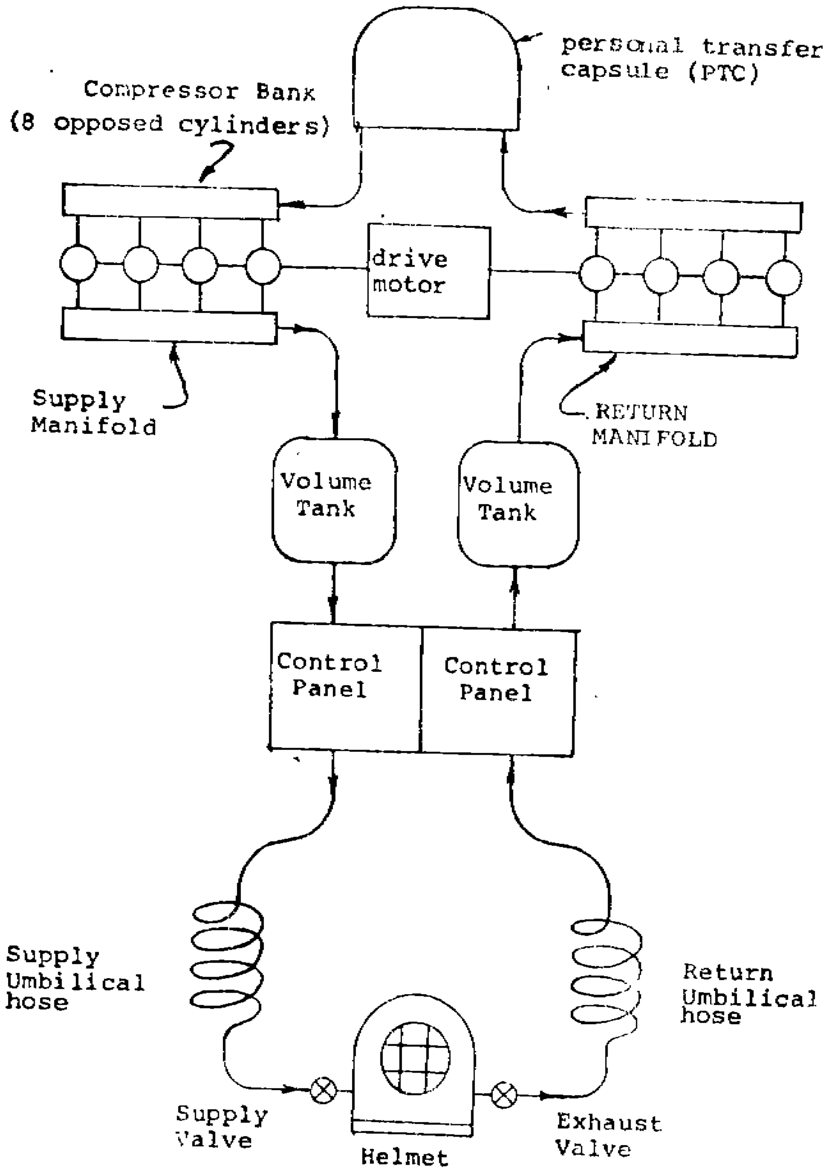


Figure 4

Breathing Gas Circuitry



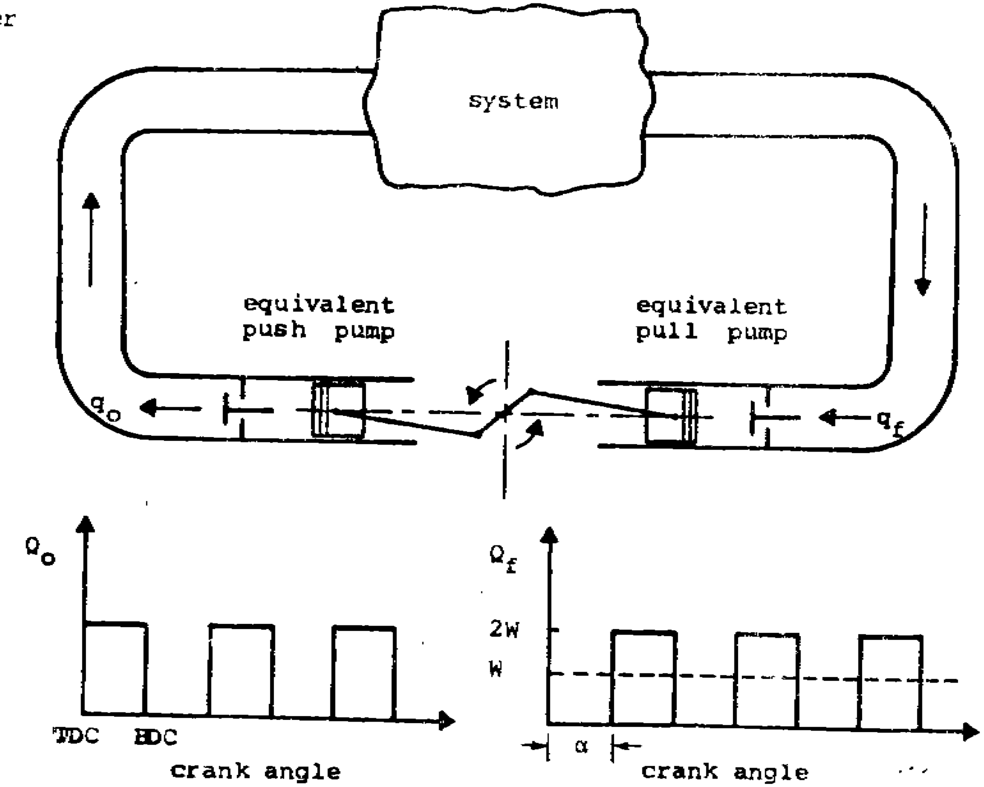


Figure 5. Push and pull pumps modeled as single compressors with square wave outputs and kinematic phase lag α.

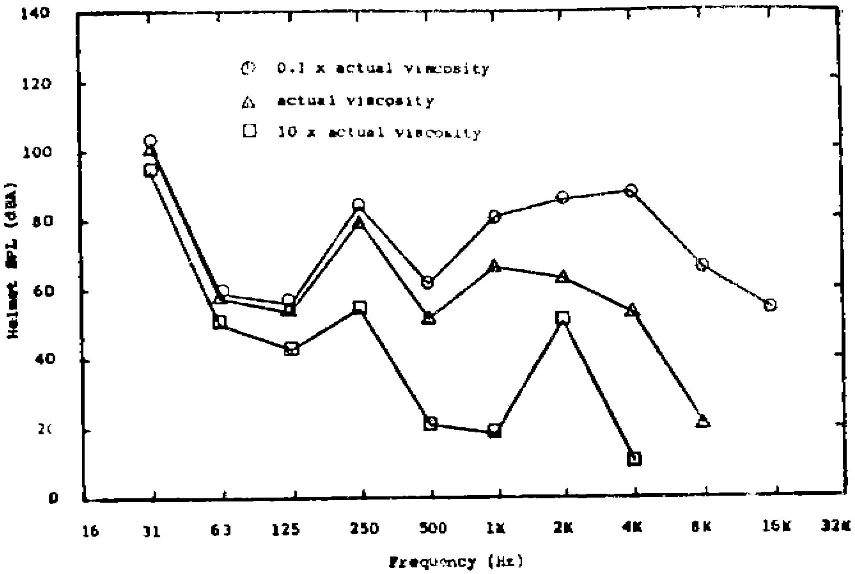


Figure 6. Effect of viscosity of breathing gas. (diving system at 200 feet depth).

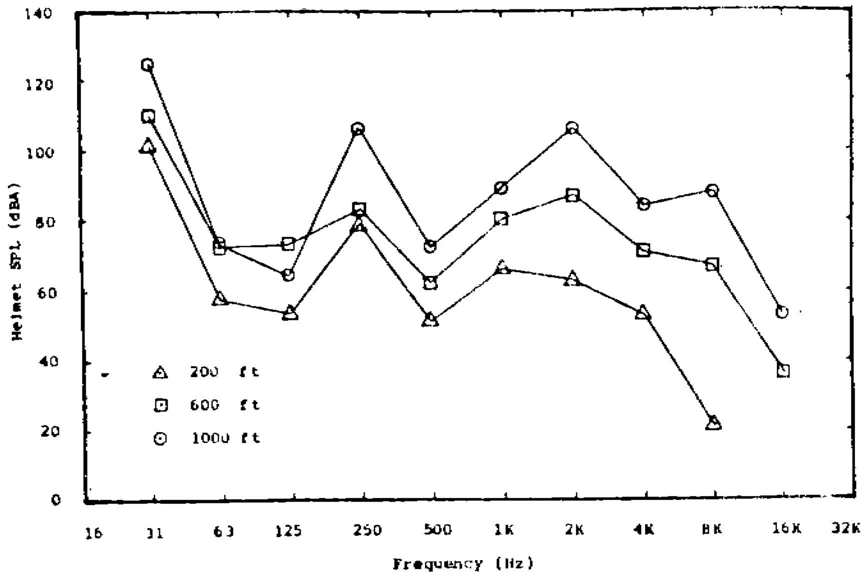


Figure 8. Effect of diving system depth.

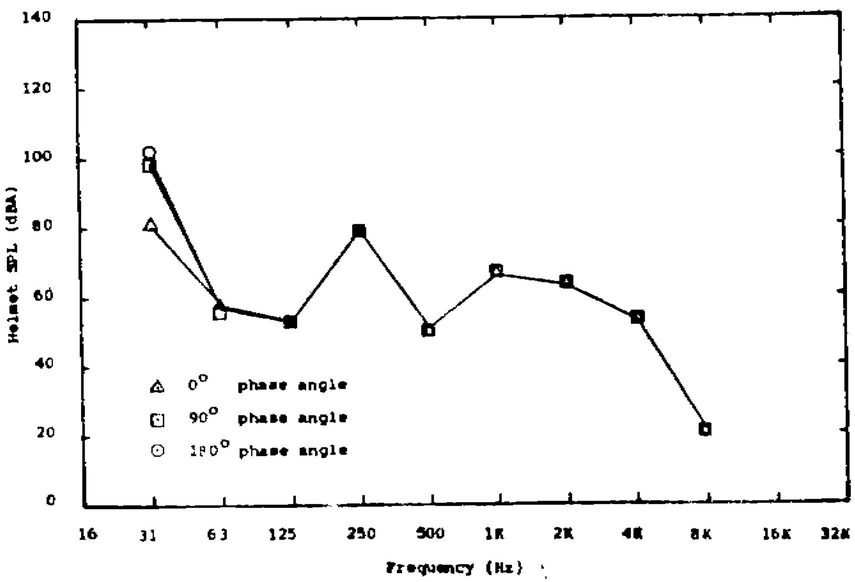


Figure 7. Effect of phasing between compressor banks. (diving system at 200 feet depth).

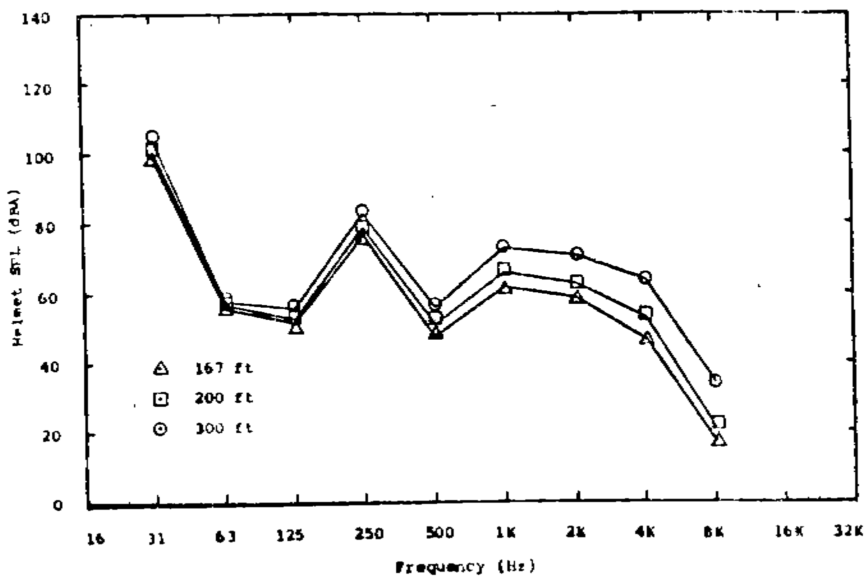


Figure 9. Effect of divers depth relative to the PTC. (PTC at 200 feet depth).

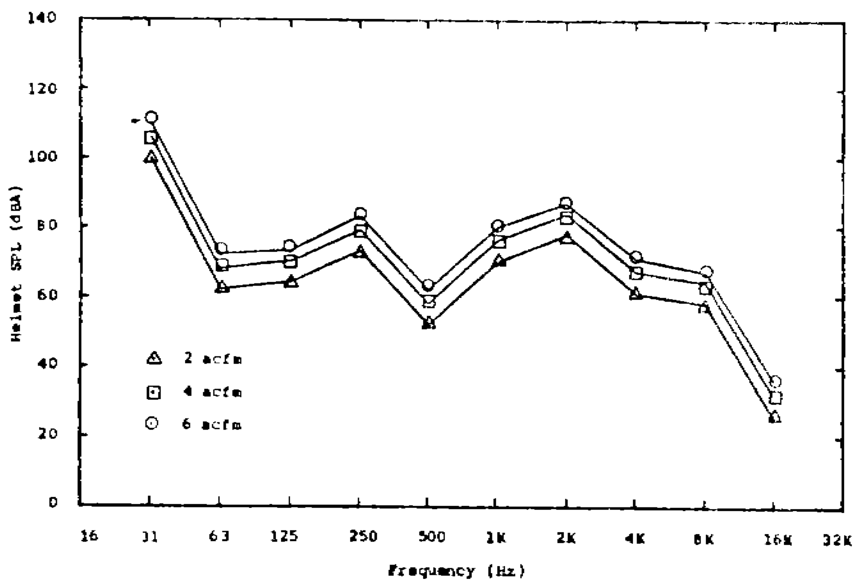


Figure 10. Effect of breathing gas flow rate. (diving system at 600 feet depth).

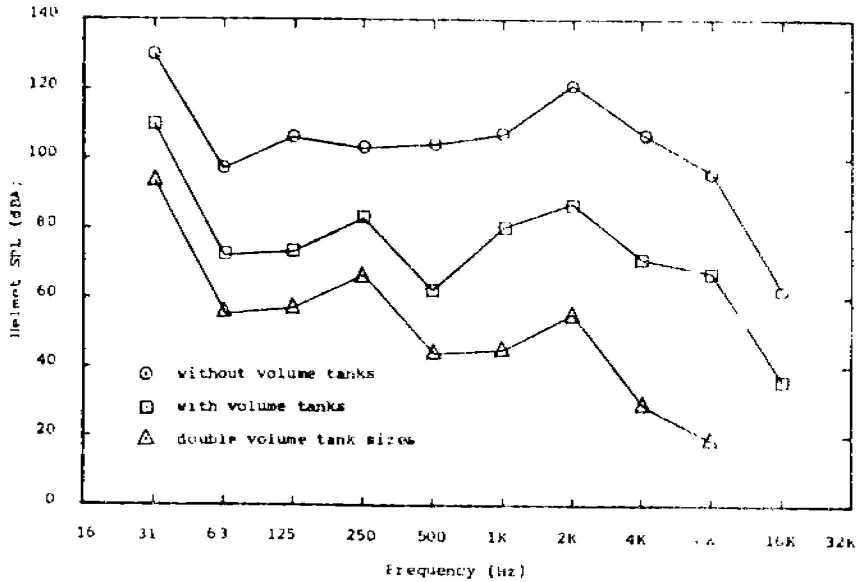


Figure 11. Effect of volume tanks. (diving system at 600 feet depth).

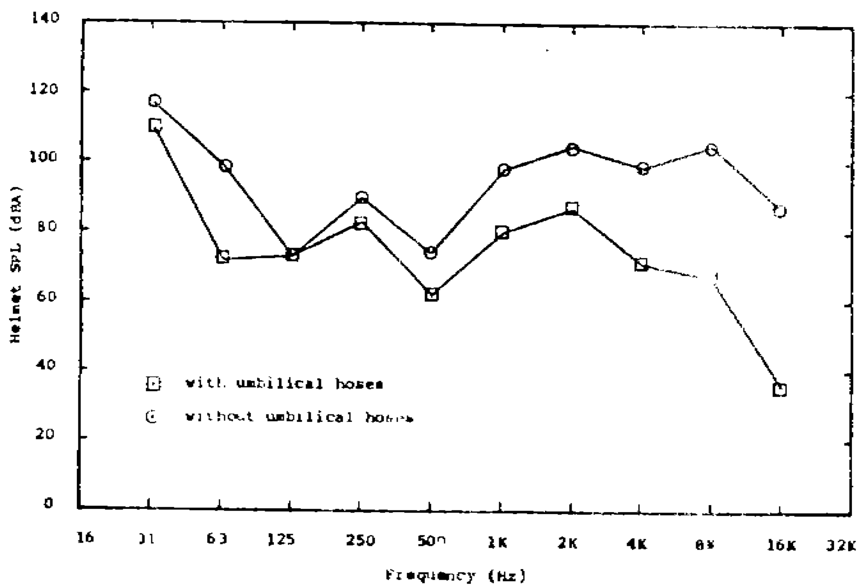
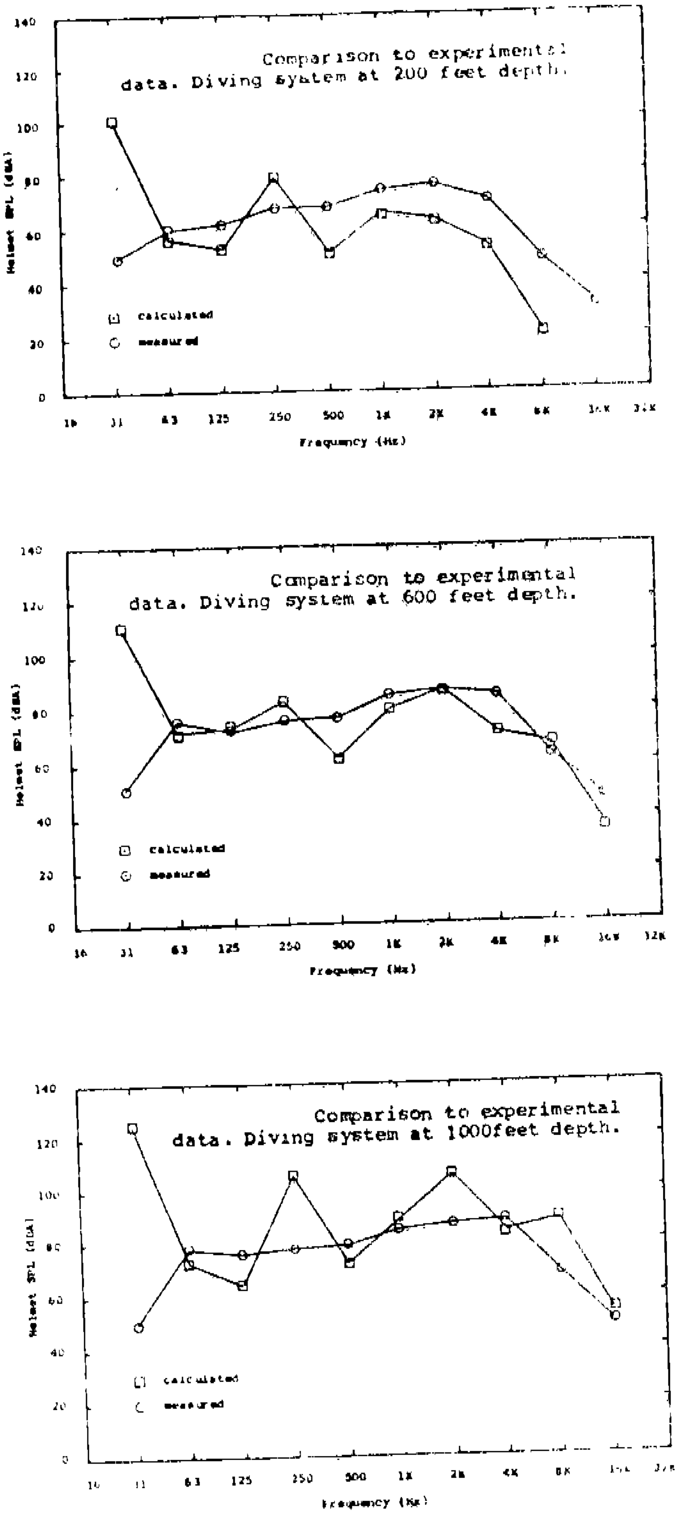


Figure 12. Effect of umbilical hoses. (diving system at 600 feet depth).



(a)

(b)

(c)

Figure 13